An integration architecture for process manufacturing systems

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Abstract. Given the significant differences between discrete and process manufacturing industries, specific integration architectures are required to accommodate the unique characteristics of process industries. In this paper, an architecture that encompasses view models, flow models and O-O models is developed, which gradually specifies the evolving design details through successive lifecycle stages of process manufacturing systems. In the architecture, products are distinctly modelled to reflect the impact of product data and to facilitate the development of customized products. A combination of object and agent concepts is adopted for building the models of process manufacturing systems. System constituent elements are respectively modelled as two types of entities: namely the objects and agents. Objects are used to describe the passive constituent entities that possess no autonomy and conduct no functions, whereas agents are used to model the active entities that possess decision-making capabilities and perform operations on objects. One important advantage of the architecture is that it provides executable models at the implementation stage, which can be directly converted into application programs coded in object-oriented languages. Some models of the architecture are further discussed in depth and an information infrastructure based on CORBA standards is proposed for integrating the distributed data sources.

1. Introduction

According to forms of material flows in production processes, manufacturing industries are classified into discrete and process (continuous) manufacturing industries. Process manufacturing industries cover many sectors, such as pharmaceutical, food, metallurgy and petrochemical engineering, and play a very important role in a nation’s economic strength. There exist large differences between discrete and process manufacturing industries in the production and business processes. The end products are made by material cuttings and component assemblies in the discrete manufacturing industries. The production processes are divided into discrete stages, where the work-in-process can be deferred in buffers between stages, whereas in the process industries, the raw materials continuously flow through a set of pipelined equipment until they are transformed into end products and by-products. For instance, the final products of petrochemical industries are obtained through various chemical reactions such as splitting, combination, distillation and fraction. These production processes run continuously and the material flows cannot be interrupted before completion. In this paper, the terms process manufacturing systems and process manufacturing companies are interchangeably used to refer to companies in process industries.

Process manufacturing companies have considerably benefited from the research efforts and implementations of the technologies mentioned above. For instance, in 1980s, the petrochemical industry widely implemented the distributed control systems (DCS) in oil refineries, most of which have operated steadily. With the increasing automation performance of facilities, process industries have shifted emphasis to managerial matters. In addition, many production planning and scheduling systems have been developed to improve the competitiveness of process companies in terms of time, quality, costs and services (Artiba and Riane 1998, Blomer and Gunther, 1998, Loos and Allweyer 1998). Problems in the process industries were usually tackled separately, in accordance with specific technical or management domains. However, many problems are not easily decoupled into simple technical
or managerial sub-problems, and solutions to these complicated problems require knowledge from multiple domains. The disciplinary isolation of managerial and technical implementations gave rise to the obstacles for process manufacturing systems to achieve the global performance optimization.

Nowadays, intensive changes and the fierce market competition compel process manufacturing companies to break through these obstacles by integrating management strategies, human factors, production processes and control techniques. Computer integrated manufacturing that has been successfully applied in discrete manufacturing industries is also gaining wide acceptance in process industries. Turbulent changes are demanding that companies change their conventional ways of running businesses, shifting from a continuous production mode to a market-oriented batch production mode. To achieve integration of managerial and technical elements, companies are resorting to architectures and reference models in order rapidly to build specific integrated manufacturing systems. The most well-known system architectures in the 1990s include CIMOSA (Jorysz and Vernadat 1990a, b), GRAI, and Purdue Engineering Architecture. However, research efforts have been interminably devoted to looking for new architectures, in order to accommodate the changing environmental conditions, recent technical advances and requirements of new manufacturing paradigms. A recent research paper describes a structured approach through which an enterprise model and modelling methodology can be developed to support the modelling requirements for new manufacturing paradigms (Toh 1999). Roberts et al. (1999) present a virtual plant modeler (VPMOD), which formally characterizes and integrates chemical product designs, batch-chemical equipment (plants), the real-time scheduling of chemical batches, and the control of chemical transport through the plant.

Architectures not only provide models representing different aspects of systems, but also provide approaches for integrating data sources. Today’s information integration involves heterogeneous data sources distributed across company borders. To support interoperability in a heterogeneous environment, the components of a system are normally defined as distributed objects and packaged as independent pieces of code that can be accessed by remote clients by method invocations (Chen and Hsiao 1997). Currently, the Common Object Request Broker Architecture (CORBA) from the Object Management Group (OMG) and the Distributed Component Objective Model (DCOM) from Microsoft are two industrial standards that are often used to build integration infrastructures in the distributed heterogeneous environments. Comparatively, the CORBA receives much more interest from academic researchers. The CORBA service specifications provide transaction management services, including remote database access, interoperability and distributed object transaction.

In this paper, an architecture for process manufacturing systems is developed, which consists of five views and certain process models to meet the specification requirements of different development stages. It is argued that, in general, architectures with a constitution of the function, information, resource and organization views, have been found to be sufficient (Toh 1999). However, it is extremely important to pay attention to the products in today’s changing markets. Product structures, features and processes to fabricate the products exert dominant influences on business performance, organization structures, information processing and resource utilization. Therefore, a product view has to be included in the architectures, in order to reflect changing customer demands, to manage the product data efficiently, and to provide customized products. The architecture provides a framework embodying organizations, functions, processes, resources, products, and their interrelationships. Process integration deals with the global optimization of a variety of processes occurring in the enterprises, such as material flows, energy flows, capital flows, human flows, etc. Hence, a number of process models have been incorporated to facilitate the process integration. Finally, a CORBA-based information infrastructure is proposed to provide services for integrating distributed data sources.

2. An integration architecture for process manufacturing systems

Performance optimization of process manufacturing systems demands socio-technical integration of organizations, management, product developing, planning and scheduling, process control, etc. The goal of socio-technical integration of a process manufacturing system is to ensure that (1) all the equipment and facilities operate in safety and in full capacities, and (2) the whole system maintains a long, stable and optimal performance period against external disturbances. In addition, specific architectures have to be developed to support achieving the socio-technical integration in process industries.

2.1. Requirements on integration architectures

Architectures are frequently used for modelling and implementing large complex systems, such as
control systems, information systems, manufacturing systems, etc. An architecture is the compendium of a large complex system, describing the interrelationships among components and the stages of system evolutionary trajectories. It is used to unify various component modules at different spatial levels and temporal stages, presenting the system as a holistic whole. Specifically, it specifies user requirements and system designs, and supports system implementations, operation and maintenance. Recognizing the significance of architectures, researchers are continuously improving existing architectures and probing for new ones.

Methodologies are important factors that influence the development of a specific architecture. The structural analysis methodology is the basic approach of dealing with large complex systems, and reducing complexity by decomposing the interdependencies among system elements. For a long period, the structural analysis methodology, characterized by top-down decomposition, dominated the developments of architectures. A number of reference architectures that support this top-down approach have been proposed, and most notable amongst these are CIM-OSA, PERA, GRAI and ARIS (Edwards et al. 1998). Today, the distributed object-oriented methodology is increasingly used to avoid the disadvantages caused by the hierarchical decomposition of structural analysis methodologies. Object-oriented techniques provide a new way of thinking about problems through models organized around real-world concepts (Chen and Hsiao 1997). It is believed that new architectures have to be developed on the basis of assimilation of both structural analysis and object-oriented concepts.

Architectures should have a high flexibility of being reconfigured to adapt to specific industrial situations. They should also simultaneously be comprehensive to capture all the basic contexts of systems and they should be easy to learn and to implement in industrial scenarios. Architectures must be integrated, consisting of a variety of elementary models and dynamically reflecting system changes over time courses. Architectures normally consist of multiple view models to represent different aspects of the complex systems. Architectural views are generally represented by using different modelling approaches. A modelling approach is the language of symbols, semantics and grammars, which describes the real-life systems, including its internal relationships among components and its external relationships with the environments. Modelling should focus on the critical factors while omitting the trivial details. Integration and navigation among the view models should be carefully considered in developing architectures.

2.2. View models of process manufacturing systems

The number of views, or the aspects of focus, is of extreme significance in developing architectures. In this paper, it is believed that five views are necessary to represent the basic aspects of function, information, organization, product and resource in process manufacturing companies. As shown in Figure 1, the five views comprehensively describe the main facades of process manufacturing companies, and both the internal and external relationships.

Products are the physical objects developed by the manufacturing systems to meet customer demands. Hence, a view on the product aspect will indicate the environmental requirements and the internal response to these external requirements. Functions are the very activities that transform raw materials into products and perform managerial transactions. In a macroscopic level, the function view describes the system functionalities. Information is the very data that support the function executions and an information view generally specifies the ways in which data are accessed, stored, processed and transferred. The organization is a structural framework of human beings that actively carry out various activities; thus, an organization view casts a light on human factors and their interaction with technical factors. Resources are the assets, including facilities, that can be used to help human beings to complete their jobs. A resource view is required to support the optimal configuration and reconfiguration of manufacturing resources.

Furthermore, a variety of flow models can be derived by examining the dynamic interrelationships between these view models. For instance, the processes with which organizations perform functions are modelled as the workflows. The processes with which information is handled to support function executions are modelled as the information flows. The sequences of functions that transform raw materials into products strongly correlate with the material flows. Capital flows are derived by associating costs to material consummations, facility utilization and human performance.

In addition, the five views describe clearly the relationships between process manufacturing systems and their environments. From the viewpoint of products, markets characterized by customer demands exert great influence on product development processes. Products are ordered by customers, produced and then delivered to customers. The product view transmits customer requirements to all organization units of a company, which improves service and increases the customer satisfaction. With regard to organizations, human employees are not isolated components of manufacturing systems, they are also
active entities of the social systems. Hence, many social factors influence behaviours of the employees, and these social factors need to be well managed. Information exchanges with environments are basic conditions for a manufacturing system to maintain vitality. The capability of exploring various external information sources cannot be overestimated in today’s changing markets. In addition to the conventional communication means, companies are increasingly collecting and disseminating information over the Internet. In the context of resources, the raw materials, facilities, and energies are the input from the environments and the constituent components of a process manufacturing system.

2.3. Integration architecture for process manufacturing systems

Based on the postulations above, an architecture for process manufacturing systems is proposed, which consists of two-dimensional axes indicating, respectively, the lifecycle stages and the concentrated aspects. As shown in figure 2, along the horizontal axis, a system lifecycle is divided into four stages: requirement analysis, preliminary design, detailed design, development and operation. The initial three stages are the concerns of this paper. Along the vertical axis, a process manufacturing system is represented by the correlated models, which are continually transformed through the lifecycle stages to capture the design details required.

As aforementioned, a process manufacturing system is first modelled, at the requirement analysis stage, by five view models. The function view represents all the business and production activities, covering the decision-making support, management, planning, scheduling, operation and control. The information view represents information collecting, processing, transmission, etc. The IDEF0 and IDEF1x are common methods for respectively describing function and information aspects of large manufacturing systems. The organization view depicts the organization structure, organizational entities, and their interrelationships. Organization views can be represented by charts and tables. The resource view depicts the attributes of enterprise resources, such as status, specifications, capacities, and classifications. Resource views are frequently recorded in tables. The product view depicts the product characteristics, such as recipes, processing approaches, equipment required, etc. The product view has to provide a standard format to describe the end products, by-products, wastes, etc. The product view model integrates products tightly with information processing, resources consumption and manufacturing
activities. These view models, inheriting the merits of the structural analysis approaches, give users a global understanding of the problem scope and the conceptual images of the system constitutions.

As the view models are very general, lacking technical details for implementations, they are transformed into process models describing various flows at the preliminary design stage. Process models are developed by abstracting the interdependencies among the activities. The process models cover the information flows, material flows, workflows, etc. Each category of process model can be further refined to reflect specific flows. These flow models comprehensively reflect the most important constituents of process companies in terms of the human, capital, material, supply, product, and sales factors. A major task in developing a systematic approach to studying processes is to conceptualize clearly an appropriate unit of analysis. ‘Event’ is an appropriate label, and is traditional for studying elements of a process in process philosophy (Peterson 1998). The process models have to embody the mechanisms and rules that support the task decomposition, function coordination, conflict-resolution, and cooperation. Process models may be used for decision support on any levels of the enterprise organization for strategic, tactical or operational planning (Kosanke et al. 1999).

In the detailed design stage, the flow models are further refined into object models depicting various entities that move within the flows. All the constituent entities are encapsulated as objects in conjunction with agents. Agents can be regarded as a special type of object that can proactively conduct certain functionalities. More specifically, human beings, facilities and applications are modelled as agents that have capabilities, knowledge and decision-making intelligence. The control flows and workflows are designed on the basis of Multiagent systems, including various control, coordi-
nation and management algorithms, and agent interfaces. Although the interface agents and application agents are equally registered to the information infrastructures, there exist temporary and dynamic hierarchical relationships among the agents. Data, products and raw materials are modelled as ordinary objects on which operations are conducted to change their attributes. The ways and conditions for conducting operations are described by the object methods. The information flows are developed on the basis of the registered objects stored in distributed databases and the services provided by the integration infrastructures. Other flow models are designed on the basis of objects, which are controlled and managed by agents. The use of agents and objects enhances the reusability and reconfigurability of process manufacturing systems. The agent-based models allow a dynamic hierarchical relationship, reducing communication and negotiation complexity, and they also possess the advantages of quick response to opportunities.

In summary, the view models describe a process manufacturing system in the macroscopic context, in which the constituent components are represented in a large granularity. Therefore, the view models are useful in strategic analysis and decision making. The flow models describe process manufacturing in a more detailed context; the constituent components are represented in a medium granularity. The flow models are useful in tactical evaluation and design. Finally, the object-oriented models describe the system in a microscopic context, in which the components are represented in a small granularity. The object models are useful in operational analysis and implementations.

3. Organization and workflow models

Human beings are the most important and indispensable entities of process manufacturing systems, and actively dominate the system performance. To achieve global optimization, human factors need to be tightly integrated with other technical resources and processes. It is accepted that integration in organizational terms is concerned with facilitating cooperation between heterogeneous function units. Human factors have to be described by the appropriate organizational and workflow models to support the socio-technical integration. Organizational and workflow models have to enable a clear awareness of organizational goals and values, pride on the organizational membership, and high commitments on the organizational behalf. It is identified that factors leading to higher performance include higher belief in organizational goals and values, higher desire to keep membership in the organization, and higher willingness to put in effort on behalf of the organization (Gupta et al. 1998).

3.1. Organization structure modelling

Organization models are used to describe the human roles, responsibilities and their interrelationships in conjunction with management paradigms. Management paradigms are strategies for constructing organization structures in harmony with technology implementations. Management paradigms position and orient the companies in the changing markets and improve the total performance of human and technical elements. Hence, the management paradigms adopted by companies impose preconditions on organization structures. For instance, Quick Response Manufacturing (QRM) proposes that companies compete on speed and to reduce lead times, by implementing the product-based flattened cellular organization structure consisting of teams (Suri 1998). Nowadays, it is widely accepted that no one company has all the capabilities to bring complex products to market independently. To gain collective competitive advantages in the changing markets, companies are compelled to form various alliances, collaboratively providing customer-demanded products and services.

An organization model describes the organizational structures specifying human roles, responsibilities, constraints, mechanisms for task decomposition and assignments, and dynamic coordination. Recently, configuration has been used to seek consistent links between prevailing situational characteristics and relatively stable organizational structures. Implicitly, the discrete events to which organizations must respond are represented by generalized characterizations of things such as the environment, and the discrete actions organizations take are represented by generalized structures and strategies (Peterson 1998). To cope with changes, organization structures have to be capable of learning, adapting, optimization and reconfiguration. A recent study shows that the environmental uncertainty, defined as the degree to which future states of the competitive environment cannot be anticipated or predicted accurately, is a reason for portfolio restructuring (Bergh and Lawless 1998).

Traditionally, process companies implemented rigid organizational hierarchies where human employees were functionally deployed within many managerial levels. Layered organization hierarchies result in information complexity, inconsistency, and work inefficiency. These hierarchical organization structures are now receiving intense criticism for their drawback of a sluggish response to changes. Project-
oriented team organizations are gaining favour, as having advantages such as high motivation of team members, function concurrency and efficient coordination. However, pure team organization structures are extremely difficult to implement in a large company. As the employees are divided into small groups, it is very difficult flexibly to exploit various manufacturing resources. There is a danger that specialist engineers located in small project teams are deprived of the benefits of working in a department with colleagues of their own specialist discipline, namely the ability to discuss technical problems with their peers and having access to the valuable fund of general historic technical and professional data plus current awareness that such departments accumulate (Lock 1997). At present, the organizational configuration commonly adopted by process industries is the hybrid matrix structure, where human employees are simultaneously deployed into disciplinary departments and task-oriented work teams.

3.2. Workflow modelling in process manufacturing systems

The dynamic processes of the performance of organizations are popularly represented as workflows. Essentially, workflow management involves the control of performance of operations on documents in terms of (a) who can access which documents, (b) what operations can be performed on a document by a worker, and (c) how the sequence of operations should be carried out by the various workers (Kumar and Zhao 1999).

Workflows also can be modelled at different granularities in accordance with requirements on technical details. A corporate workflow model can be further decomposed into sub-workflow models; and workflow models at a lower level can be aggregated to form a corporate one. A typical corporate workflow of an oil refining company is shown in figure 3. The corporate workflow begins with crude oil selection, looking and choosing the appropriate oil sources. The suppliers of crude oils are usually selected on the basis of prices, shipping costs, oil properties, and other economic and political factors. The successive process is oil procurement, in which crude oils are purchased from the selected suppliers and shipped to neighbour-

Many workflow management approaches have been addressed in recent research literature. Most workflow management models used the concept of an event as the basic construct, of which the occurrence orders may be either static (predetermined and fixed) or dynamic (routed during execution). The Computer Support Cooperative Work (CSCW) and agent systems are two complementary approaches most suitable for supporting human collaboration. The CSCW allows for the sharing of the informal sensory space between human agents, whereas the agent-based approach enables the sharing of the formal knowledge space between software agents (Sreeram and Chawdhry 1999).

Agent-based methods are increasingly gaining favour in modelling workflows where cooperation mechanisms are of importance. According to Sycara et al. (1996), agents in a distributed system can be further divided into three groups: interface agents, task agents and information agents. The interface agents mainly collect information from users to initiate tasks and present the results and explanations. After task specifications from the interface agents, task agents formulate problem-solving plans and execute problem-solving activities in cooperation with other agents. Information agents have knowledge of the data sources and strategies for information selection, access, conflict resolution, and information fusion. Information agents provide interface agents and task agents with the exact information required.

4. Product models and material flows

4.1. Product data model

In discrete manufacturing industries, product data are usually described by bill-of-materials, drawings and
CAD files. In process manufacturing industries, product data are usually described by recipes. Hence, product models in process industries have to be modelled with a concentration on the recipes. The Instrument Society of America has defined four levels of recipes that can be found in an enterprise, namely: general, site, master, and control recipes (Verwater-Lukszo 1998).

The object-oriented approaches are suitable to construct the product models in both discrete and process industries. The fundamental construct of object-oriented approaches is the object that encapsulates the data and associated operations to be performed on the data. As shown in figure 4, objects are used to encapsulate all the material related elements such as crude oils, additives, end-products, by-products, and waste discharges. The non-relational information, such as customer specifications, may be documented as files to be associated with the corresponding objects. The objects of recipes are then used to specify the interrelationships among the material related objects. A general recipe defines a product ‘configuration’ by specifying crude oils, additives, its co-products, waste discharges, etc. The general recipe provides the product information that describes the common production processes. The general recipe may be shared by many process companies, as it does not specify the equipment to be used.

Derived from a general recipe, a site recipe is a product formula specific to a particular site (e.g. a refinery). A site recipe adds site-specific information to a general recipe. A site recipe needs to take into account customer specifications, specific properties of the raw materials to be used, and batch-production schedules. A site recipe also needs to comprise the data concerning balance between loads and capacities in the production site. A master-recipe is equipment-dependent and provides specific and unique batch-execution information describing a product that is to be produced in a given set of equipment. As operations in facilities have to be controlled, a master recipe must provide reference to equipment models. Finally, a control recipe is obtained by adding real-time operation information to a master recipe. The control recipe contains detailed process operation data and equipment control parameters, such as temperature, humidity and flux. The control recipe is production batch specific and contains the information exactly used in the production processes.

4.2. Material flow model

As materials in process manufacturing systems are described as objects, material flows reflect the
processes that change the attributes of these objects. The basic attributes of material objects, which are to be changed through various physical regulations and chemical reactions, include flux, quantities, purity and properties. Figure 5 illustrates a material flow model of a chemical plant, where equipment resources are described as agents and materials as objects. From the beginning, the objects of salt brine are input into the agent of the electrolytic bath, which continuously decomposes the salt brine into objects of sodium caustic (NaOH), hydrogen (H₂) and chlorine (Cl₂). The object of sodium caustic is consecutively changed into objects of liquid sodium caustic and solid sodium caustic by agents of the vaporizer and the boiling vessel. In parallel, objects of the hydrogen and chlorine are combined into the object of hydrochloric acid (HCl) by the agent of the synthetic tower. On the other branch, the objects of calcium carbide, hydrogen and chlorine are successively changed into objects of polyvinyl chloride (PVC) by the agents of the converter, fractionating tower and the polymerizer. The model can be used to track material flows, simulate production scenarios, and support optimal scheduling.

5. Information integration infrastructure

5.1. Challenges to information integration

Effective management of information sources poses continuous challenges to manufacturing companies. The wide applications of computers in nearly all the organizational units have created an explosive amount of information. Heterogeneous data sources are built in isolation, and the various local networks for process control and production management are not interconnected. Information cannot be exchanged and shared because of a lack of standard information classification and coding systems. Insufficient access to necessary information often results in poor performance and reduces competitive advantages. For example, in a petrochemical company, the raw oils are directly charged into production facilities from oil ships, causing instability of production processes and wastes because the production planning departments have no access to information about the raw oils stocked inventories and the raw oils en-route. Production plans and schedules were manually developed by experienced professionals, without the help of the
optimal algorithms and access to accurate data about current production status.

Therefore, information integration within and across company borders becomes necessary to increase company competitiveness. Integrating multiple information sources in the distributed heterogeneous environments is a challenging task. Over the past two decades, CIM involves integration of multiple predetermined applications and data sources located within company borders, where designers can keep track of the applications and information sources to be integrated. Nowadays, the rapid emergence of increasing Internet-based services is permeating the company boundaries and greatly shaping manufacturing industries. Internet developments offer sophisticated communication and information transfer services supporting market exploration, electronic commerce transactions, and collaborative manufacturing among geographically dispersed organizations. Companies are forced to integrate efficiently the dispersed data sources beyond the company borders. The challenge is that designers have no earlier knowledge of numbers and types of the data sources to be operated, and have no control of application systems that are to be added to and/or removed from the environments.

5.2. Building data sources

Generally, information integration requires that data sources are developed to store the data objects, and that enabling infrastructures are developed to facilitate interoperability among the distributed data sources.

The first step in creating data sources is developing suitable information classification schemata. Companies have to process and exchange a vast amount of information in business processes. It is very difficult to handle the explosive amount of information without properly classifying and representing the information. An information classification schema is developed for ensuring reliability, comparativeness and unique interpretation, and for eliminating the multi-sense of data. All data are identified and divided into specific information classes, which consist of sub-classes describing different aspects of the companies. The information classification schemata are dependent on the business nature, purpose and application of the data. Figure 6 illustrates an information classification schema developed for a petrochemical manufacturing system. In this schema, information is categorized into organization, business, production and product classes. Information classes may be further decomposed until primitive information object classes are reached. The basic information objects are regarded as instances of the information classes and are coded in uniform data structures.

In addition, the second step in creating information sources is building a variety of databases to store the classified information objects. In process industries, information sources may be managed in three levels, namely the business management, production management, and control levels. The major criteria in categorizing data sources are time intervals of data processing and the data influence. The data processing frequency at the lower level is larger than that at the upper level. Data sources at the top level usually involve company-wide operations, while those at the bottom level only involve the local operation of facilities, cells, etc.

As illustrated in figure 7, in the business management level, databases have to be created to contain information about market demands, customer orders, suppliers, business plans, and finance data. A knowledge base is created to contain mathematical models and dynamic system models used in management, scheduling, and optimal control, and also solutions to these models. The knowledge base is used to support the decision-making processes at the company level. In the production management level, the resource database, crude oil property database, production database and material balance database are created. Petrochemical companies develop optimal production plans with regard to customer demands, the properties of crude oils, the capacities of production devices, storage and the capacities of public utilities. The production database includes equipment specifications, five-day plans, facility positions and production samples. Material balance databases are the basis for scheduling processes. In the optimal control level, an equipment model library and a real-time database are created. The real-time database includes real-time data collected on-site, graphical system configurations, interfaces for control systems and alarm sets. The various complex physical and chemical reactions that take place in the facilities are described by equipment models. Equipment models use sets of equations to describe equipment dynamics and constraints among equipment units, such as the input/output, context, chemical reactions and control parameters.

Obviously, the data sources at the two lower levels are directly linked with production processes. They manage the data that plan and control the production operations, and collect the data that reveal production status. The information sources at the top level are indirectly connected with the production processes. These data sources manage the data that support relatively long-term decisions. Information from the
external environments is input into the data sources at the top level. A multiple dimensional data warehouse is created by abstracting the data from sources at the upper two levels, which is used to generate various statistic reports and to reply to various inquiries.

5.3. Distributed information infrastructure

The CORBA standards are the ideal means that support distributed transactions involving multiple application objects and span multiple data sources over the Internet and company intranets. CORBA also supports transactions across heterogeneous platforms such as NT and various Unix platforms. An information infrastructure, based on CORBA standards, is developed to provide services for integrating distributed data sources. The information infrastructure is composed of four layers of services as illustrated in figure 8.

Open Interface layer: providing clients and servers with the standard application programming interface (API) and visual interfaces based on web browsers. The OMG uses interface definition language (IDL) to define interfaces for the objects to be connected with a CORBA bus. An IDL interface file describes the data types and methods or operations that a server provides for an implementation of a given object. Information source adapters have to be developed to change heterogeneous data formats into standard formats, facilitating information reusability and system reconfigurability.

Broker layer: brokers are the middleware that enables users to access distributed data sources transparently. Brokers interpret user requests, locate the target objects and invoke methods on the objects, and finally deliver results to the requestors. In this way, the brokers create dynamic client/server relationships among the distributed objects.
Data communication layer: the communication bus of CORBA/ORB assembles, transmits and regroups data objects, completing communication among data objects.

Network interface layer: providing services that map data transmission transactions to the specific network transmission/protocols.

Figure 7. Data sources of a petrochemical company.

Figure 8. A CORBA-based integration infrastructure.
Within the integration infrastructure, data sources are encapsulated into information objects, and are defined and registered by the brokers. Information objects of data sources can be easily added and/or cancelled when the related applications take part in and/or withdraw from the environments, allowing flexibility and scalability. The application systems are encapsulated as application objects, which are connected through adapters to a CORBA-compliant object request broker (ORB) bus across the Internet and company Intranet. The underlining essence of the infrastructure is that all the information transactions are conducted with the help of the brokers. The brokers maintain the data transparency in the environments, separating application objects from the details of data access. When an application object issues a request, the brokers will find the right target data object, invoke it, deliver it the message, and return the response messages to the application object. In this way, application systems realize access to and operations on the distributed data sources.

6. Conclusions

Companies in process industries are large complex systems, which must be developed and managed under appropriate architectures in order to cope with operational dynamics and market changes. Architectures can reduce investment risks both in new system development and reconfiguration of existing systems. They also largely influence the ways in which the companies are run. Therefore, the significance of architectures cannot be overestimated in process industries.

In this paper, an architecture has been proposed to support the modelling, design, and implementation of process manufacturing systems. Under the integration architecture, the granularity of models is successively refined into three levels in accordance with the different requirements on technical details in the three consecutive lifecycle stages. Apart from the conventional views of organization, function, information and resource, the architecture develops a product view to stress that all manufacturing activities should be centred on product developments. The view models at the requirement analysis stage reveal the relatively static aspects of companies, while the flow models at the preliminary design stage demonstrate the dynamic relationships of entities that constitute the static aspects. The architecture has smoothly integrated the view models, process models and implementation models, which are used to capture and reveal system details required at different stages. In the detail design stage, all system models are transformed into object- and agent-based models, which can be directly implemented in O-O languages. The architecture also brings forth an integration infrastructure, in compliance with CORBA standards, to provide services necessary to integrate distributed data sources. The architecture enables companies to reconfigure frequently the organization structures, product lines and production processes to regulate the impacts of market changes.

It is noted that socio-technical integration and performance optimization of process manufacturing systems require interminable research efforts and many areas remain open. For instance, the organization models are to be improved to depict more explicitly the dynamic organizational behaviours. Approaches for material balance in processes, product data management, optimal resource planning, and distribution management, are future research directions.

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